Fundamentals of Nanoelectronics

Prof. Supriyo Datta
ECE 453
Purdue University

11.05.2004

Lecture 28: Minimum Resistance of a Wire

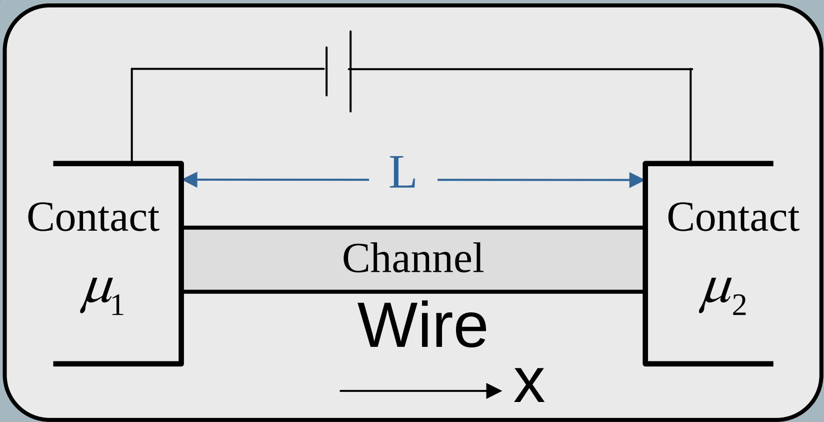
Ref. Chapter 6.3

Network for Computational Nanotechnology

NCN
nanoHUB
online simulations and more

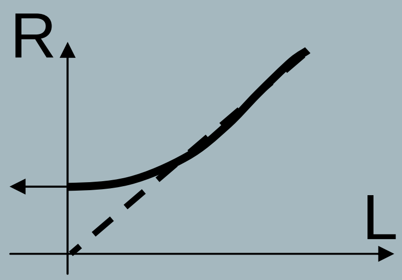
Current Carried by a Subband

00:05



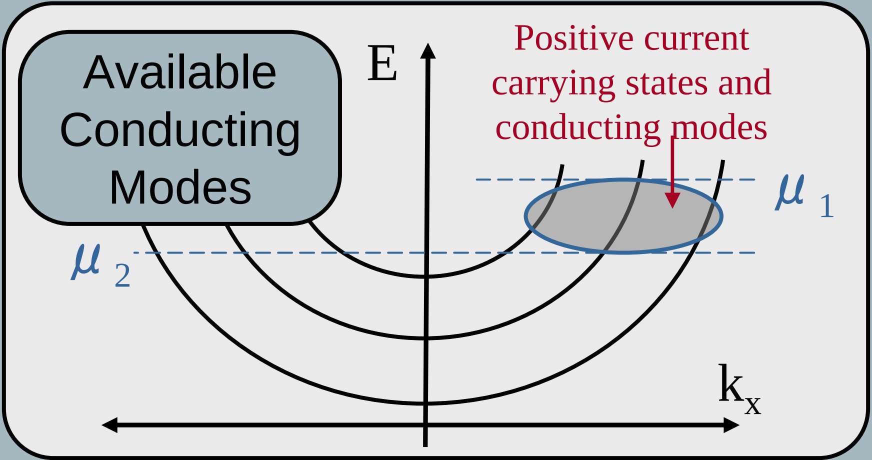
- We've been discussing minimum resistance of a 1D wire that is very short.
- One wrong argument was that R~L and as length goes to 0 the resistance should go to 0. The correct answer is that the resistance does increase but when the wire gets very short, resistance will saturate.

$$R_{\min} = \frac{h}{2q^2}\frac{1}{M}$$



- We calculated the current carried by each subband for a range of a given voltage.

$$\frac{q}{h} \cong 40\frac{\mu A}{eV}$$

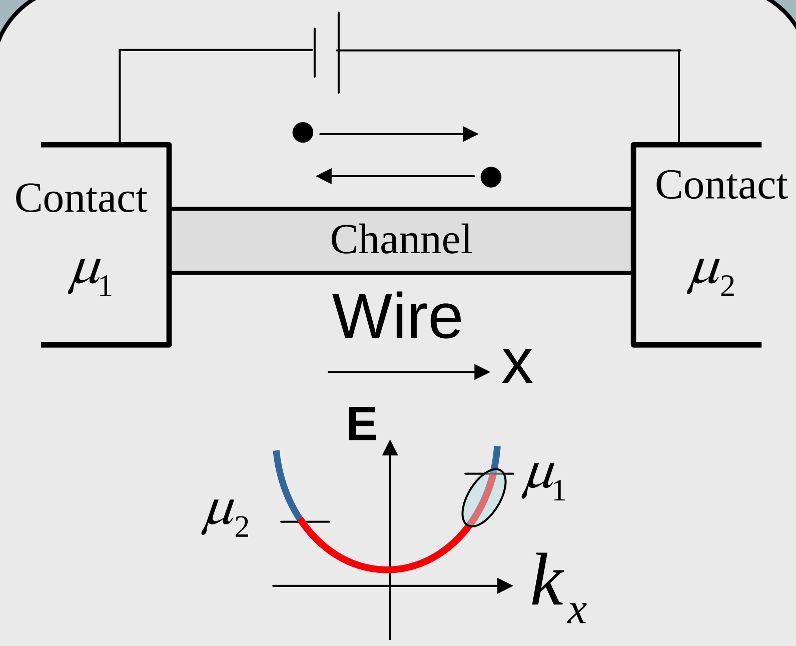


- We want to explain how this value is related to the minimum resistance…

Minimum Resistance

06:24

- Let's draw the E-k diagram at some point along the wire:



$$\mu_2 = \mu_1 - qV$$

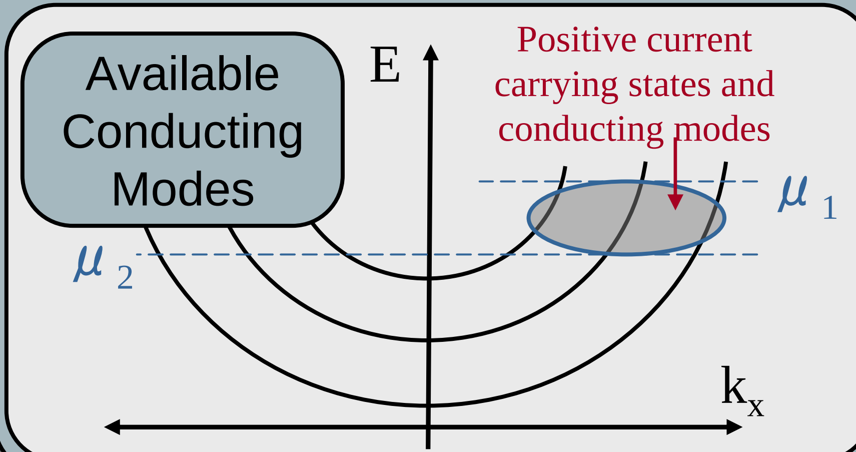
- The current in this wire can be calculated as: $I = \frac{2q}{h}(\mu_1 - \mu_2) \Rightarrow$

$$G_{max} = \frac{I}{V} = \frac{2q^2}{h} = 80\frac{\mu A}{V}$$

$$R_{min} \approx 12.5 k\Omega$$

- For several modes:

$$R_{min} \approx [12.5 / M] k\Omega$$



Number of Modes

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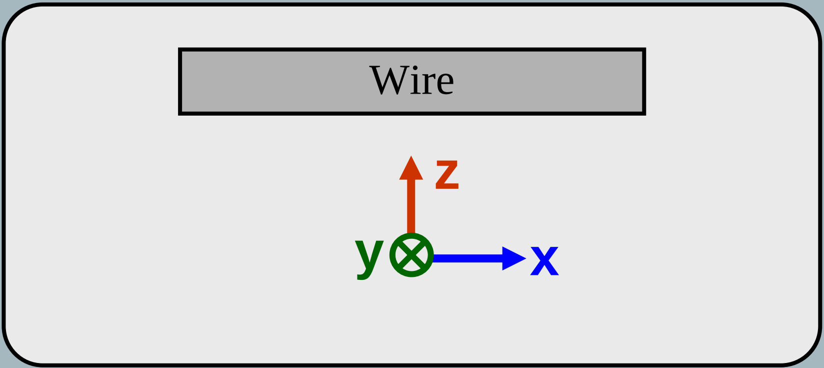
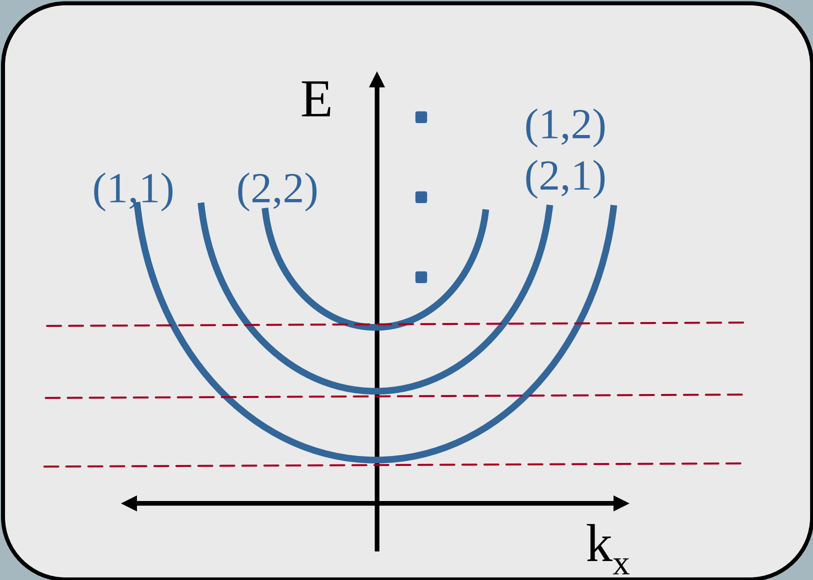


• The number of modes can be determined from the cross section of the wire. Remember the dispersion relation:

$$E = E_C + {h^2}\big/{2m_C}\left(k_x^2 + k_y^2 + k_z^2\right)$$

$$k_y = \frac{\pi}{L_y}\upsilon_y \qquad k_z = \frac{\pi}{L_z}\upsilon_z$$



• Notice that for a bigger cross section the bands get closer to each other. As the result the number of modes in the energy range of interest will increase and the resistance will decrease. Higher cross section → Lower resistance.

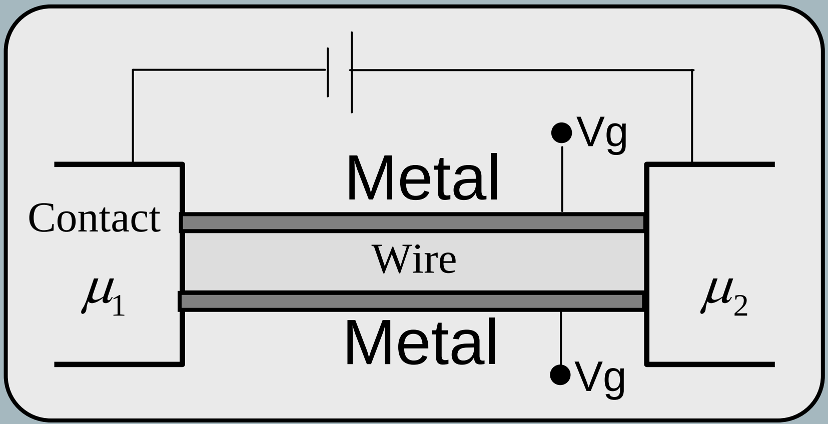
• Cross section:

Lower Resistance

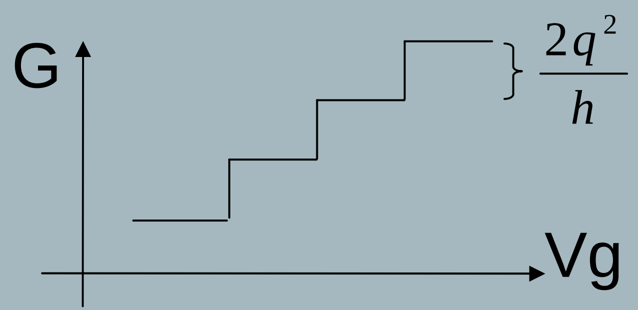
Where is the Heat Dissipated?

22:30

- The experiment that actually proved these results to be right was done in 1980's:



- The voltage applied to the metals could actually deplete the wire and make the effective cross section smaller.

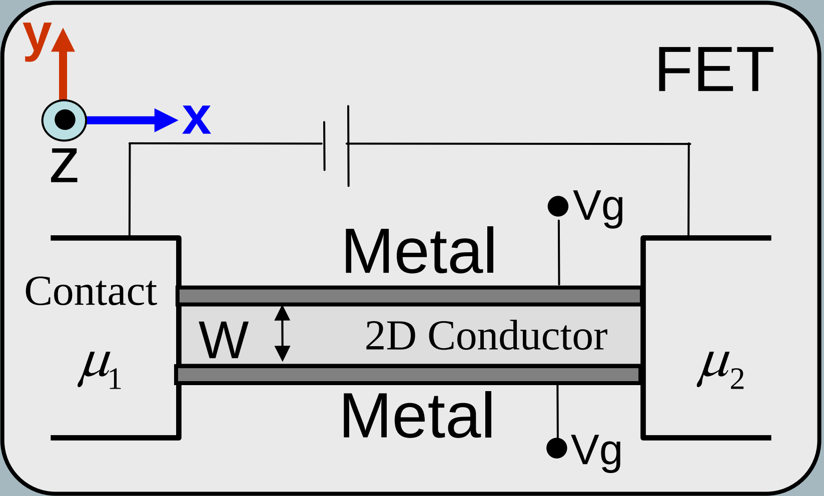


- The reason some people expected the resistance to go to 0 when the wire is very short was that for such a wire there would be no heat dissipation as electrons travel through it. Since resistance is always associated with R(I^2) they claimed that resistance should go to 0. What really happens is that although there is no heat dissipation in the wire, but there is heating in the contacts.

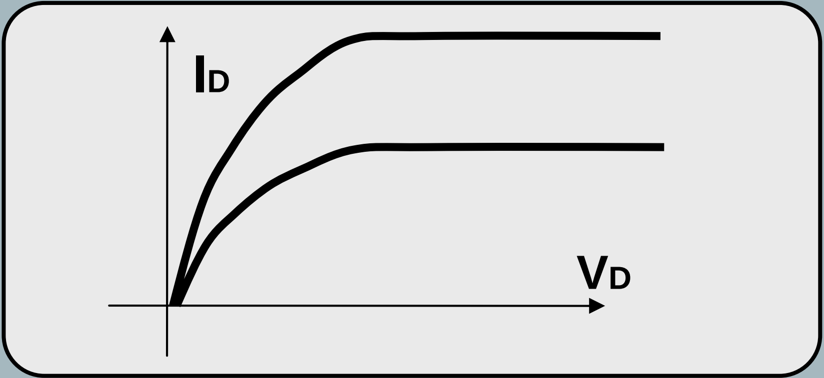
Minimum Resistance of an FET

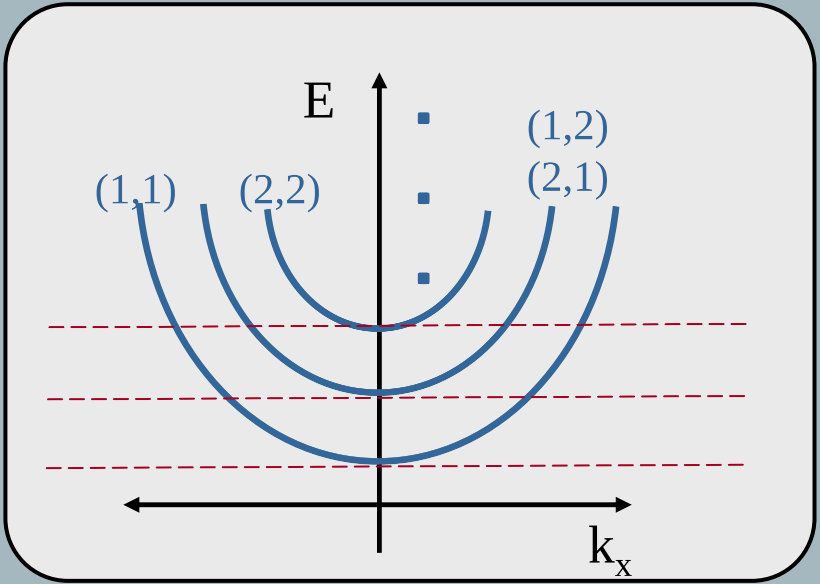
28:30

- Let's now think about a 2D conductor.



- What is the minimum resistance of this device?





- We need to know "M" to answer this question:

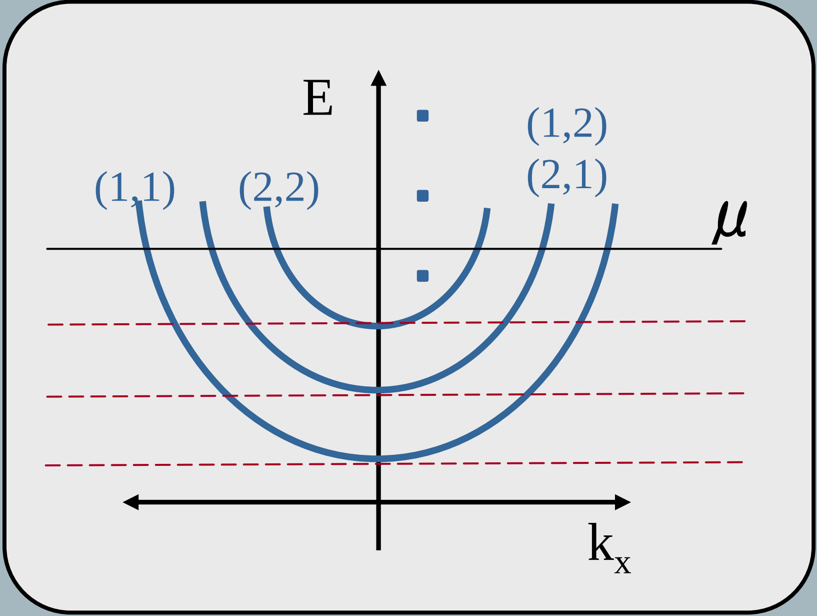
$$R_{\min} = \frac{h}{2q^2}\frac{1}{M}$$

- Let Lz to be very small. So

$$E = E_C + \frac{h^2}{2m_C}\left(k_x^2 + k_y^2\right)$$

Minimum Resistance of an FET

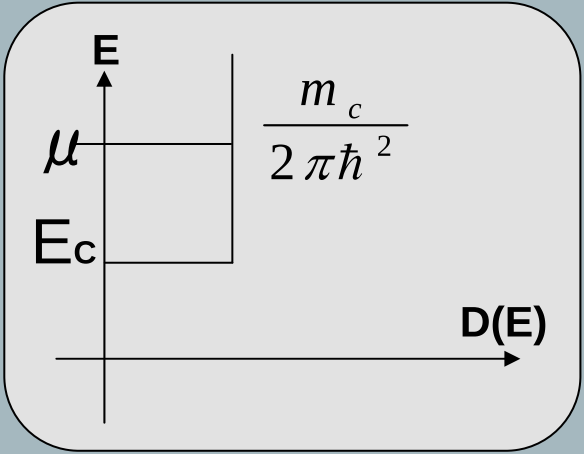
- Note that even with the best contacts, there would still be a minimum contact resistance and it is useful to know what the lower limit is.
- Consider the modes and assume that electrons are confined to lowest z subband.



- Assume Lz to be very small. We have:

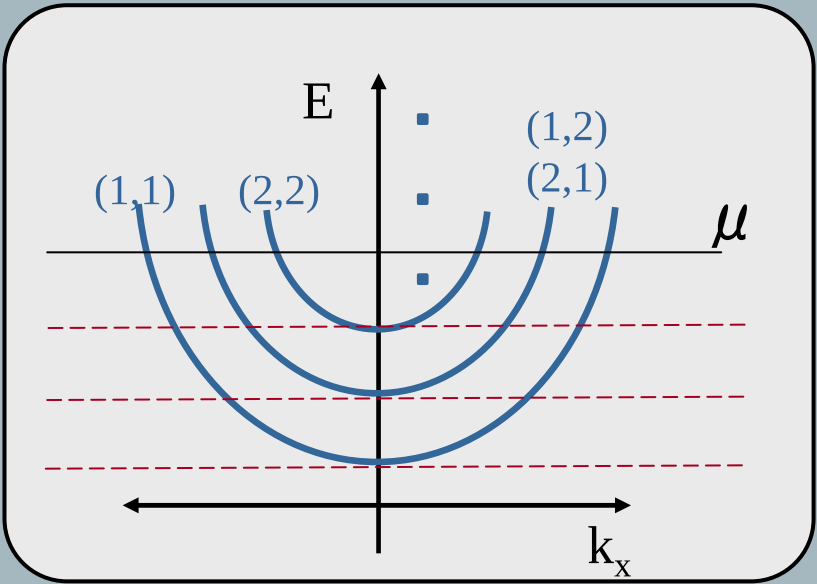
$$E = E_C + \frac{h^2}{2m_C}\left(k_x^2 + k_y^2\right) \qquad k_y = \frac{\pi}{L_y}\upsilon_y$$

- We want to the number of sub bands "M" for a given μ .



$$n_s = \frac{m_c}{2\pi\hbar^2}\left(\mu - E_c\right)$$

Minimum Resistance of an FET



$$n_s = \frac{2m_c}{2\pi\hbar^2}(\mu - E_c)$$

$$E = E_C + \underbrace{{h^2}/{2m_C}\,\frac{\pi^2}{L_y^2}\upsilon^2}_{\text{Bottom of sub band}} + {h^2}/{2m_C}\,k_x^2$$

Bottom of sub band

$$M = \upsilon_y = \sqrt{2m_C(\mu - E_C)}\,\frac{L_y}{\pi\hbar}$$

$$R_{\min} = \frac{h}{2q^2}\frac{\pi\hbar}{L_y}\frac{1}{\sqrt{2m_c(\mu - E_c)}}$$

$$= \frac{h}{2q^2}\frac{\pi\hbar}{L_y}\frac{1}{\sqrt{2\pi\hbar^2 n_s}} \Rightarrow$$

$$R_{\min}L_y = \frac{h}{2q^2}\sqrt{\frac{\pi}{2n_s}} \approx 12.9k\Omega\,\frac{1}{10^6/cm}$$

- For a transistor with the length of 1micron:

$$R_{\min} = \frac{12.9k\Omega \times 10^4\,\mu m}{10^6} \approx 150\Omega - \mu m$$